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SPECTRAL TRANSMISSION OF THE EYE

E. A. Boettner

The University of Michigan
Ann Arbor, Michigan

July 1967

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The University of Michigan

Contract AF41(609)-2966

prepared for

USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas

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FOREWORD

The research described in this report was prepared by Professor Edward A. Boettner, Department of Industrial Health, School of Public Health, The University of Michigan for the USAF School of Aerospace Medicine under Contract AF41(609)-2966 and covers the period 1 April 1966 to 30 June 1967. Research was performed under Project 6301, Task 630103, Work Unit 630103 008. Captain David J. Lehmiller USAF School of Aerospace Medicine was the contract monitor. Because it is the third phase of a program to determine the spectral transmittance of the human eye, extensive summaries of the first two phases are also included for the purpose of consolidating the data of the entire program.

The three phases were supported and monitored as follows:

Phase I. Transmission of the Ocular Media. Contract AF33(616)-6847. Initiated by the Vision Section, Protection Branch, Life Support Systems Laboratory of the 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The contract monitor was Major Donald G. Pitts, USAF, BSC. Period of contract: 1 December 1959 to 1 December 1961.

Phase II. Transmission of the Human Eye. Contract AF33(657)-8880. Initiated by the Vision Section, Protection Branch, Life Support Systems Laboratory of the 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Later transferred to the USAF School of Aerospace Medicine, Brooks Air Force Base, Texas. Contract monitors: Major Donald G. Pitts, USAF, BSC; Lt Col Benjamin Kislin, USAF, BSC; Captain David J. Lehmiller, USAF. Period of contract: 15 March 1962 to 14 August 1965.

Phase III. Transmission of the Eye. Contract AF41(609)-2966. Initiated by the USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas. The contract monitor was Captain David J. Lehmiller, USAF.

Professor Edward A. Boettner, Department of Industrial Health, School of Public Health, The University of Michigan, was the principal investigator throughout the entire program. Professor J. Reimer Wolter, M.D., Department of Ophthalmology and Department of Pathology, The University of Michigan Medical School, was the co-principal investigator during the first two phases, and was a consultant during the last phase. Dr. Josephina Sevilla and Mr. John Nelson did the dissecting of the monkey eyes in the last phase of the program under Dr. Wolter's tutelage.

Animal experiments were performed in accordance with "Rules Regarding Animal Care" established by the American Medical Association.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

ABSTRACT

The spectral transmittance of ultraviolet, visible, and near infrared light through the eye of humans and monkeys has been measured. Using freshly enucleated eyes, the transmittances of each component part (cornea, aqueous humor, lens, vitreous humor, retina and choroid) were determined for the wavelength range from 0.22 to 2.8 μ (microns). Two types of measurements were made: the first to measure the total light transmitted (direct and scattered) at each wavelength and the second to measure the percent transmittance of that light passing directly through the various media without absorption or scattering. The results show that: (a) the transmission of ultraviolet radiation decreases with the age of the eye; (b) the transmission of infrared radiation appears to be independent of the age; and (c) the maximum total transmittance of the whole eye, about 85%, is obtained in the region from 600 to 850 mμ (millimicrons). The spectral reflectance of the fundus and sclera of the rhesus monkey was measured, with the former reflecting less than 2% in the visible but increasing to 20% in the infrared (1200 mμ). The sclera reflects 20 to 30% through the visible and infrared out to 1200 mμ. The forward scattered light outside of 1 degree as measured on the whole human eye was 35% ± 5% at 566 and 666 mμ.

I. INTRODUCTION

This report is concerned with the transmission and reflection of ultraviolet, visible, and infrared radiation in the human eye. Such information is important to many researchers concerned with the eye and its use (1), and it is of especial concern to those engaged in the study of the physio-pathological effects of luminous energy on the eye (2,3).

One of the first investigators to concern himself with the transmission of the eye was Brucke, who investigated the reason for the invisibility of ultraviolet rays. Later others investigated the visible and infrared portions of the spectrum. Duke-Elder summarized the work in this field up to 1952 very thoroughly in both Volumes 1 and 4 of his textbook (4). In this summary, most of the measurements reported have been made on animal eyes, especially those of the rabbit (5) and steer (6). The human data was that reported by Ludvigh and McCarthy (7) in 1938, giving measurements in the visible region of 4 human eyes of average age 62 years, all with sarcoma of the choroid. Recently, Geeraets and co-workers (8) measured 7 eyes, only 2 of which could be termed normal.

Because of the dearth of transmission information on human eyes, a research program was begun in 1960 and continued until 1967, the aim of which was to determine the transmission characteristics of the eye in vitro for electromagnetic radiation in the ultraviolet, visible, and infrared region. The program was divided into three phases. The first phase was to determine the transmission of the individual ocular media, i.e., cornea, aqueous humor, lens, and vitreous humor. Phase two was devoted to measuring the transmission of the composite ocular media, and phase three was concerned with measuring the transmission of the components of the fundus and the reflection from the fundus. The measurements were made on 16 enucleated human eyes and on numerous eyes of rhesus monkeys. The monkey eyes were used to establish and evaluate the measuring technique. They also provided substantiating information in statistically weighing the human data, because of the anatomical similarity of monkey and human eyes. This report is arranged according to the three phases of the work. In addition, the measurements on monkey eyes are described and compiled in the Appendix.

When electromagnetic radiation passes through a medium, several things can happen to the radiation: (1) It can pass directly through the medium (called direct transmittance in this report); (2) It can be reflected by the medium; (3) It can be scattered by the medium. In this case, all the radiation passing to the medium also emerges, but in random directions; (4) It can be absorbed by the medium. All four of these phenomena take place when radiation passes through the eye. Some of the energy passes directly through to form an image in the retina. Some is scattered by the media, resulting in a general

illumination within the eye (9). Some is absorbed and reradiated at longer wavelengths. A small amount is reflected by surfaces separating media of different refractive indices. Most of the reflection takes place at the anterior surface of the cornea, which is the boundary with the greatest change in index of refraction.

In this report, two sets of transmittance measurements are described. One is a measure of direct transmittance and the other is a measure of both the direct and a portion of the scattered. The aperture which limits the direct transmittance measurements is so arranged that it accepts only the rays of the direct beam and those within about 1 degree of the direct. The total transmittance reading is a measure of all the radiation emerging over a cone of about 170 degrees centered about the optical axis. This measurement includes that radiation which is forward scattered. It does not include the portion of the radiation that is back scattered (that portion which is reflected back into the same hemisphere as the original incoming beam).

II. TRANSMISSION OF THE INDIVIDUAL OCULAR MEDIA

A. Experimental Procedure

The transmittance of the components (cornea, aqueous, vitreous, and lens) of nine human eyes was measured in the first phase of the work. These eyes were determined to be normal pathologically by the pathologist* who prepared the specimens for measurement. The mounting and measuring techniques were first worked out with the use of the eyes of rhesus monkeys. Monkey eyes were also used for preliminary observations of the effect of time after enucleation on the transmittance measurements.

The procedure for preparing the individual components for measurement and the measuring techniqu s are described in detail in reference 10. A Beckman DK-2 spectrophotometer was used to measure the direct transmittance and the total transmittance was measured with a Beckman DK-1 spectroreflectometer. The measurements were made from 220 mμ in the ultraviolet to 2800 mμ in the infrared.

B. Results

Nine human eyes, at ages 4 weeks, 2, 4-1/2, 23, 42, 51, 53, 63, and 75 years respectively, have been measured. Figures 2 and 4 show the transmittance of the aqueous and the vitreous humors. These data have been averaged from the measurements on several eyes. The curves of the cornea and the lens (figs. 1 and 3) are of specific eyes in order to show the effect of age on the transmittances. The data of figures 1-4 are tabulated in table I.

Cornea. This component transmits radiation from 300 mμ in the ultraviolet to 2500 mμ in the infrared (fig. 1). The total transmittance increases rapidly from 300 mμ and reaches about 80% at 380 mμ, and from 500 mμ to 1300 mμ is greater than 90%. Beyond 1300 mμ, two absorption bands of water appear (1430 and 1950 mμ) but the transmission between the bands remains high.

The total transmittance curve is representative of 6 eyes, with the spread in the values at 700 mμ of less than 3% with no age trend.

Two direct transmittance curves are shown, with the lower near the average of 8 eyes and the upper curve (fig. 1) the best transmittance observed. The maximum transmittance of the direct measurements is at 1100 mμ. The cornea is the only component having its maximum this far in the infrared.

*Dr. J. Reimer Wolter, see Foreword.

Aqueous Humor. This component begins transmitting at 220 mμ in the ultraviolet and continues to 2400 mμ in the infrared (fig. 2). In the ultraviolet, it has a strong absorption band at 265 mμ which some investigators (11) have attributed to nucleoprotein. Through the visible region, the aqueous has a high transmittance, slightly less than that of an equal thickness of water. Its transmittance in the infrared is decreased by water absorption bands at 980, 1200, 1430, and 1950 mμ. The transmittance at 2200 mμ is only 0.1% and the complete absorption beyond 2400 mμ is due to water. No differences in transmittance due to age were noted for this medium. Only the direct transmittance is reported since no difference could be found between the direct and total transmittance measurements. Visual observation of the aqueous after removal from the anterior chamber also shows no evidence of light scattering. However, a small amount of scattering (less than 2%) could be present and still escape detection by either method.

Lens. Transmittance through the lens extends from the ultraviolet to an upper limit at 1900 mμ in the infrared (fig. 3). The ultraviolet and short wavelength visible light transmittance varies considerably with the age of the eye. The lens of the young child begins transmitting at 300 mμ; however, an absorption band centered at 360 mμ reduces the transmittance to a very low value below 390 mμ. Because of this absorption band, the lens of a child has a transmitting band centered at 320 mμ of about 8% under 5 years and less than 0.1% by the age of 22 years. This same transmittance band was found in the lenses obtained from monkey eyes. The total transmittance of the young eye begins increasing rapidly about 390 mμ, and reaches 90% at 450 mμ. The rate of increase is considerably slower for the older lens, e.g., a 63 year old lens begins transmitting at 400 mμ but does not reach 90% total transmittance until 540 mμ. In addition, the light scattering by the older lens is much higher. The direct transmittance of the young lens at 700 mμ is about 88%, while the 75 year old lens measured only 41%. The lens continues to have a high transmittance to 1400 mμ in the infrared and demonstrates the usual water bands at 980, 1200, and 1430 mμ.

The age dependence in the visible region is in fairly good agreement with the findings of Said and Weale (12) on the direct transmittance of the lens in the living eye. For example, their curve for the 21 year lens is very close to our data (curve 1) in the region from 450 to 600 mμ. Likewise, their data for the older lens lie between our curves for the 53 year and 75 year eyes. However, it has been our experience that the older eye shows a larger variation in the amount of transmitted radiation in the visible. As an example of this variation, the lens of a 71 year eye measured had a direct transmittance better than that of the 53 year eye (curve 2 of fig. 3).

Vitreous Humor. The vitreous transmits from 300 mμ in the ultraviolet to 1400 mμ in the infrared (fig. 4). Its ultraviolet total transmittance increases rapidly to 80% at 350 mμ. The total transmittance in the visible region is greater than 90%, but begins dropping rapidly in the infrared. The water bands at 980 and 1200 mμ are very strong, and no transmittance is noted beyond 1400 mμ. No difference in transmittance due to age were noted.

Transmittance of the Entire Eye. The data shown in figures 1 to 4 were used to compute the successive transmittances as radiation passes through the whole eye. The resulting curves are shown in figures 5 and 6. In making this computation, the loss due to reflection of normally incident radiation at the interface between air and the cornea was included. Reflection losses between the other surfaces (e.g., aqueous-lens) were neglected as they total less than 0.3%.

These data are representative of the child or young adult eye except in the ultraviolet (less than 380 mμ) where the transmission is that of a child's eye. For example, the 4% incident on the vitreous (fig. 6) at 320 mμ would be completely absorbed by the lens in the adult eye.

The maximum transmittance through an entire eye is calculated as 83.5%. It is evident that the amount of scattered radiation through the young whole eye, represented by the difference between curve 4 in figure 5 and figure 6, decreases with wavelength, from about 55% at 450 mμ in the visible to 30% in the infrared. Generally the scattering in the older eye starts at a higher figure (70% or more) in the visible, but proceeds at a more rapid rate of decrease into the infrared. Table II is a compilation of the data of figures 5 and 6.

C. Discussion

Several factors may affect the validity of the results, including the condition of the eyes, the length of time between enucleation and the measurements, and the accuracy of the instrumental methods and measuring techniques. As stated previously, only eyes having normal refracting media were used in this study. Four eyes had melanoma of the choroid, with the refracting media appearing normal in all respects. The other 5 eyes had no pathologic abnormalities. All measurements were made in the time interval between 15 and 210 minutes after enucleation.

The effect of time after enucleation was carefully studied on 3 monkey eyes and 2 human specimens. Contrary to the results of Boynton and DeMott and their associates (9,13), only a little time effect was found. However, they attribute the change to a drying out of the specimen. In the work described here, the components were placed in sealed cells so that evaporation was negligible.

The only measurable change with time was noted in the transmittance of the aqueous humor in the vicinity of 230 mμ in the ultraviolet. There is an isolated transmission band at this wavelength (fig. 2) separated from the longer transmitting wavelengths by an abosrption band at 265 mμ. The amount of absorption at this latter wavelength decreases with time, resulting in an increase in the height and a slight shifting to longer wavelengths of the trans-

mission band at 230 mμ. For example, the aqueous of one monkey eye measured 1.9% at 232 mμ 30 minutes after enucleation. A subsequent measurement at 3 hours showed a transmittance of 4.2% at the peak, which shifted to 236 mμ. Likewise, one human eye measured 1.1% at 235 mμ 40 minutes after enucleation and 1.9% at 240 mμ at 4 hours.

Through the remainder of the spectrum any change with time was less than the reproducibility of the measuring technique. It should be noted that any transmission change in the first few minutes after enucleation would not have been detected in these experiments as the first readings were made at 15 minutes or more after enucleation.

Tests were carried out on the technique of measuring the cornea, because of Maurice's (14) observation that stressing the cornea could increase the amount of light scattering, thereby decreasing the direct transmittance. Measuring the cornea in two ways, first by mounting it without any distortion, and second, by using our technique of gently flattening it, no change in direct transmittance was noted. Because of the fragile nature of the thin quartz windows, no attempt was made to apply excessive pressure to substantiate the observations of Maurice.

The transfer of the vitreous humor to the measuring cell presented a problem because of the ease with which pigment from the posterior iris surface will transfuse into the vitreous as the vitreous is being removed from the eye. Very small amounts of this pigment have a depressing effect on the direct transmission measurements of the vitreous, enough so that it was obvious that these measurements on 2 of the eyes must be discounted. In the final phase of this program, when measurements were made on the ocular media of the eyes of rhesus monkeys (Appendix), the technique for removing the vitreous was refined so that pigment contamination was no longer a problem. The resulting measurements showed the total transmittance values changed very little, but the direct transmittance now approached to within a percent of the total at the peak wavelengths. Using the same techniques on human eyes, it is possible that there may be an increase in the maximum direct transmittance. However, on the basis of the scatter measurements made on the whole eye as described in Section III, it is doubtful that the increased transmittance would be as much as realized on the monkey eyes.

III. TRANSMISSION AND SCATTERING OF THE ENTIRE EYE

A. Experimental Procedure

Measurements of the various components as described in Section II made it possible to compute the direct and total transmittances of the whole eye. However, because of the possibility of accumulative errors, it was decided that measurements should be made on the whole eye to verify or disprove the calculations, and the second phase of the program was devoted to this task.

The method chosen (13) was to make the measurements by first passing a collimated beam of light through the enucleated eye in the manner and the direction that the eye normally uses for observing an object at infinity, and then scanning and measuring the image formed by the eye. To do this, the retina, choroid and sclera at the back of the eye were replaced by an optically transparent window, permitting the light to emerge and form an external image. A cell for mounting the eye was designed for this purpose; it is shown schematically in figure 7. Immediately after enucleation, a Flieringa ring was attached to the back of the eye for supporting purposes. The eye was then placed in the cell as pictured, and the choroid and sclera behind the ring were removed. A quartz cover plate was placed over this opening, in contact with the vitreous humor, and clamped to the rest of the cell, thus forming an airtight enclosure. The area between the eye and the cell was filled with saline solution, both to provide support and to keep the cornea moist. A cell with the eye in place is shown in figure 8.

The transmissometer used for scanning and measuring the image is shown schematically in figure 9. It consists of three parts: (1) a source of light, (2) a device for positioning and moving the eye and (3) a photometer arrangement for measuring the light emerging from the eye. The light source is a small tungsten lamp in an air-cooled housing, with a collimating lens for imaging the lamp at infinity. The collimator contains a limiting diaphragm 3 mm. in diameter to act as an artificial iris by limiting the amount of radiation passing through the eye. Also mounted on the collimator is a filter holder to permit the insertion of interference filters for controlling the spectral region measured. The section of the transmissometer used to hold an eye cell is made so that the eye and its cell can be rotated to any desired or measured angle with respect to the beam of light entering the eye. In addition, there is adjustment to permit one to position the eye laterally with respect to the incoming beam so that the light enters symmetrically through the iris of the eye. The photometer portion consists of a photomultiplier tube whose output is amplified and measured with a Photovolt Photometer, Model 520. The photomultiplier tube housing is mounted in back of a 0.12 mm. aperture at the rear of the eye, with adjustment available to position this aperture in the focal plane of the eye and to scan the aperture in the focal plane. Its position in the focal

plane is converted to angular measurements from the geometry of the arrangement. The image is scanned with the photocell aperture in one plane only. To examine other planes, it is necessary to rotate the cell holding the eye. The output of the photocell can be either read directly from the photometer indicating meter or recorded on a strip chart recorder.

Immediately after enucleation, the eye was moved to the laboratory and mounted in its cell, and measurements were started as soon as possible, generally 45 minutes to an hour after removal of the eye. The first measurements made were of the total transmittance for various spectral regions, generally 466, 566, and 666 mμ. To make the total transmittance measurements, the limiting aperture in front of the photocell was removed so that all of the radiation emerging from the back of the eye entered the photocathode. The signal produced by the light emerging from the eye at each of these wavelengths was compared with the signal coming directly from the collimated source when the eye and its cell were removed. This ratio, corrected for reflection losses at the cell windows, was used as the measure of the total transmittance. In these measurements, precautions were taken that the illuminated area of the photocathode was the same, both in size and position, in both cases so that variations in the sensitivity of the photocathode surface did not affect the measurements. However, tests of the photocathode surface of the particular tube used showed it to be quite uniform in sensitivity. After the total transmittance was measured, the pinhole aperture was positioned in front of the phototube and was moved along the optical axis to the position of best focus for the eye. This was determined by positioning it for maximum signal output from the photometer. Once the aperture was positioned in the focal plane, it was scanned across the image by use of a micro-manipulator, and the signal output was measured for every 9 minutes of displacement; data were taken as far as 3.0 degrees from the optical axis, at which point the photometer signal was too small to be read. Two scans were made, the second in the plane 90 degrees to the first. Another scanning technique used was to mount the aperture and the phototube as a unit and then rotate them both around the eye. This procedure was cumbersome and not very practical because of the difficulty of locating the aperture in the focal plane without the micro-manipulator. After the transmittance and scatter measurements on the eye were made, the eye cell was removed and a similar set of measurements were made on an "artifical eye," a simple glass lens whose focal length, 35 mm., was chosen to correspond to that of the eye in its cell. This longer focal length results from having the anterior surface of the cornea in saline solution rather than air. By using this lens and its transmittance and focal length, a reference or standard for evaluating the performance and stability of the transmissometer was provided.

B Results

Five eyes were measured in the program reported here. These were all pathologically normal eyes, enucleated to permit operative procedures about the eye. The amount of data obtainable on each eye was usually limited by

the number of measurements that could be made within the first three or four hours after enucleation, after which changes in transmission of the specimen became measurable. The data on each eye are given in table III. Included in figure 10 are profiles of the scatter pattern of the glass lens used for standardization and the calculated profile of a "perfect" lens. This was obtained on the basis of a 0.12 mm. aperture scanning a 0.3 mm. uniform image. The total transmittance measurements are summarized in table III. These measurements were corrected for reflection losses from the cells and although they were taken at an optical path length of 17 mm., the results were converted to transmittances that would be obtained if the path length were 21.5 mm. to make them comparable with the work described in Section II. The values include the reflection loss from the anterior surface of the cornea. Also included in table III are the corresponding calculated transmittances as given in table II.

C. Discussion

The total transmittances reported in table III are very close to the previously calculated data at 566 mμ and 666 mμ, which is near the point of maximum transmission (see figure 6). However, near the short-wavelength-cut-off of transmission (466 mμ), the measured values are considerably less than calculated. Because the transmission at this wavelength can be very age-dependent, it is expected that some measurements on specimens in the 20 to 30-year category would result in a better agreement. The measured values at 800 mμ are lower than calculated, and it is surmised that this is due to a discrepancy of the calculated values stemming from inaccuracies in the placement of the shoulder of the 1000 mμ water band.

The scattered data are in good agreement with those calculated at the two wavelengths measured. The measured scattering outside of 1 degree for the five eyes was 35% ± 5% at the two wavelengths. The calculated value from table II is 36% at 566 mμ. The data obtained on both scattering and total transmittances were limited to the few wavelengths reports, for two reasons. First, the region of greatest interest is in the spectral region of maximum transmission, and it was here that most of the measurements were made. Second, it was important that all measurements be made as soon after enucleation as possible. Any further testing of any one eye would have made the test period much too long.

Many investigators have made scatter measurements of one type or another, generally to determine the contribution of the elements of the eye to the glare mechanisms. The work in this field to 1962 has been well summarized by Vos (15). The measurements of scattering have been generally carried out in one of three ways: psychophysical experiments (16,17); methods using the ophthalmoscopic principle of passing light into the living eye and using the reflected light to measure the scatter (18,19); and direct measurement of the transmission of light passing through an enucleated eye (13,20). In our work, using the last mentioned technique, the experiment was designed to determine the validity of our previous measurements of direct and total transmittance.

IV. TRANSMISSION AND REFLECTION OF THE FUNDUS

A. Experimental Procedure

The third phase of this research was concerned with determining the disposition of radiation that reached the posterior surfaces, and measurements were made of the transmission of the retina and choroid and the reflectance of the fundus surface and the sclera.

The transmission of the retina and choroid was carried out in a manner similar to that used on the cornea. The specimens were separated from the whole eye shortly after enucleation and mounted between parallel quartz plates in a clamping cell. What is called retina here is that portion forward from and excluding the pigment epithelium, while the "choroid" is actually the choroid and the pigment epithelium. The separation was done in this manner because of the ease of parting at this junction, and to provide transmission information through the rods and cones. The entire cell was then mounted in the spectrophotometers for both the direct and total measurements. The retinal measurements presented no problems, but the opacity of the choroid limited the extent of the measurements in the ultraviolet and visible.

Spectral reflection measurements were made off the composite surface of the retina, choroid, and sclera. They were made by taking the rear of the eye and putting in a few radial cuts to permit flattening the surface. This surface was held flat against a plate by covering it with a heavy paper diaphragm. The opening in the diaphragm was aligned with the reflection sample port of the integrating sphere on the spectroreflectometer, so that the beam of radiant energy was incident on the specimen. The same technique was used for reflection measurements off the sclera after first removing the retina and choroid by careful scraping.

B Results

No human data have been obtained to data, but such measurements will be made when normal human specimens are available. However, both transmission and reflection measurements have been made on the retina, choroid, and fundus of monkey eyes, and these data are given in figures 15, 16, and 17, and tables VI and VII of the Appendix. Because of the similarity of the data of the ocular media of the monkey and human eyes, it is surmised that this similarity would extend to these tissues as well. On the basis of a visual examination, one difference that may exist is a lesser transmittance of the choroid of the adult human eye, as the pigment epithelium appears to be heavier and/or thicker than that of the monkey eye.

APPENDIX

In the course of our program, considerable use was made of monkeys' eyes to develop measuring techniques, because of their availability and similarity to human eyes. Because the monkey is frequently used in experiments involving their eyes, we have compiled our data on these animals for the purpose of transmitting this information to other investigators. These data include measurements of the transmittances of the individual ocular components and the reflections of the fundus and sclera. The specimens were prepared in the same manner as described in Section II of this report for the transmittance measurements. In table IV will be found data on the individual components, and these data are also presented graphically in figures 11 through 14. Table V gives the calculated transmittances resulting from these measurements.

The data in table IV were accumulated from 16 eyes and the data for each component are based on at least 6 sets of measurements of which the standard deviation was less than 5%. The values in table I are in reasonably good agreement with those in a previous report (22), except for the direct transmission measurements of the cornea and vitreous. Here the more recent measurements are higher, and in the case of the vitreous this is attributed to improved skill and technique in removing the fluid without pigment contamination. The reason for the higher direct transmittance readings of the cornea is not readily explained, as the technique and the methodology were the same.

The transmittances of the retina (minus the pigment epithelium) and the choroid (including the pigment) of monkey eyes were measured and these data are tabulated in table VI and plotted in figures 15 and 16. In figure 15 and table VI, although both total and direct transmittances are reported, it is suspected that the rapid change in the "transparency" of the retina after death has already reduced the direct transmittance values considerably (21). Figure 16 shows a composite of two direct transmittance curves for the choroid-pigment combination, with the dotted line shown below 1400 mμ representing the results obtained in one young monkey eye having a choroid brown in color. This choroid was similar in appearance to that noted in young human eyes early in the program. The spectrophotometer as used was capable of measurement down to 0.03%. The removal of choroid presented a difficult dissection task, to avoid introducing holes or thin spots in the pigment surface. However, the infrared band at 1445 mμ provided a good check on this, as a hole or thin spot will result in a transmission above zero.

Total reflection measurements were made of the fundus and sclera, using the technique described in Section IV. The data obtained are plotted in figure 17 and tabulated in table VII. These data have been corrected to eliminate the specular reflection between air and the moist surface of the specimens.

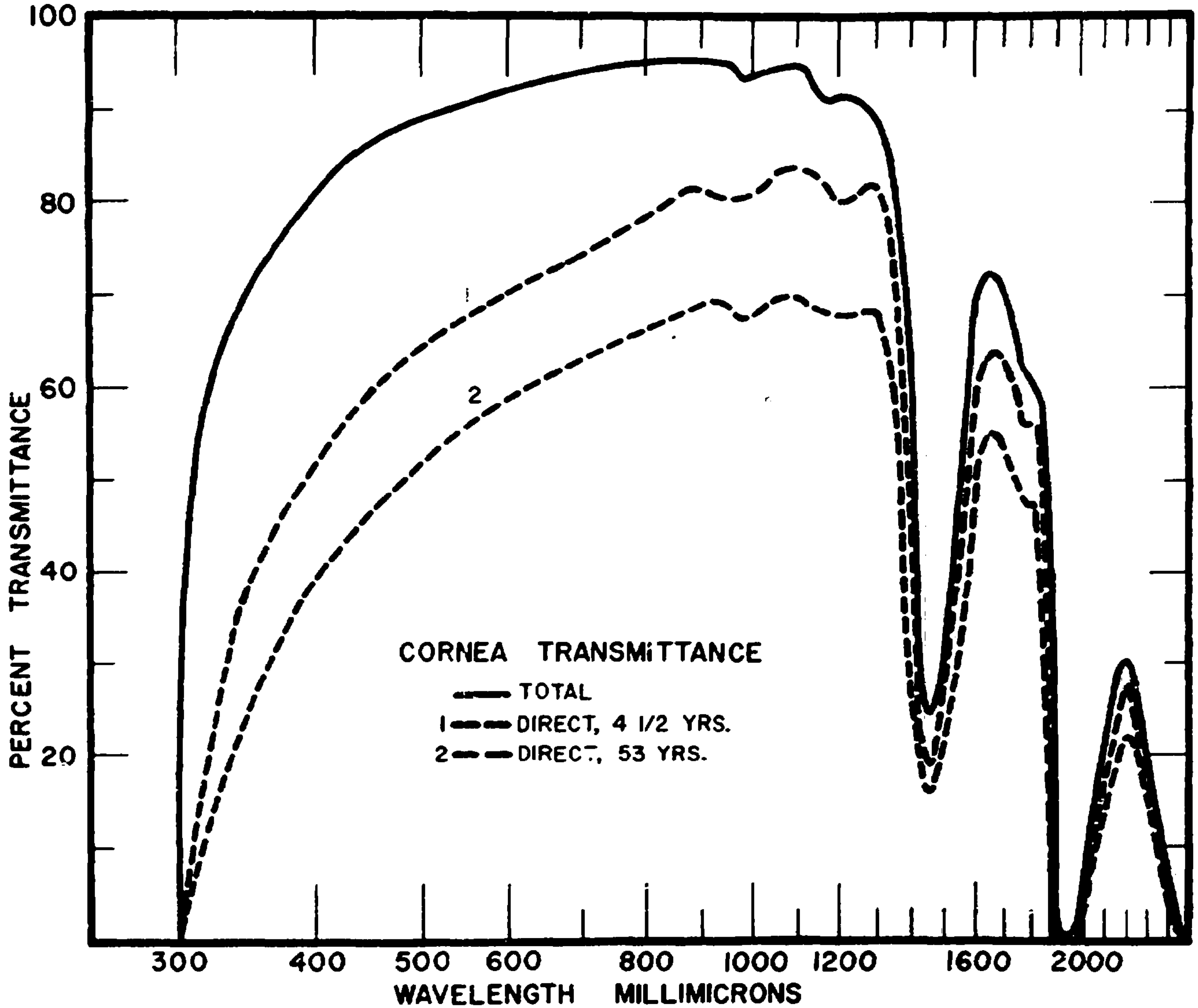


Figure 1. Transmittance of the cornea.

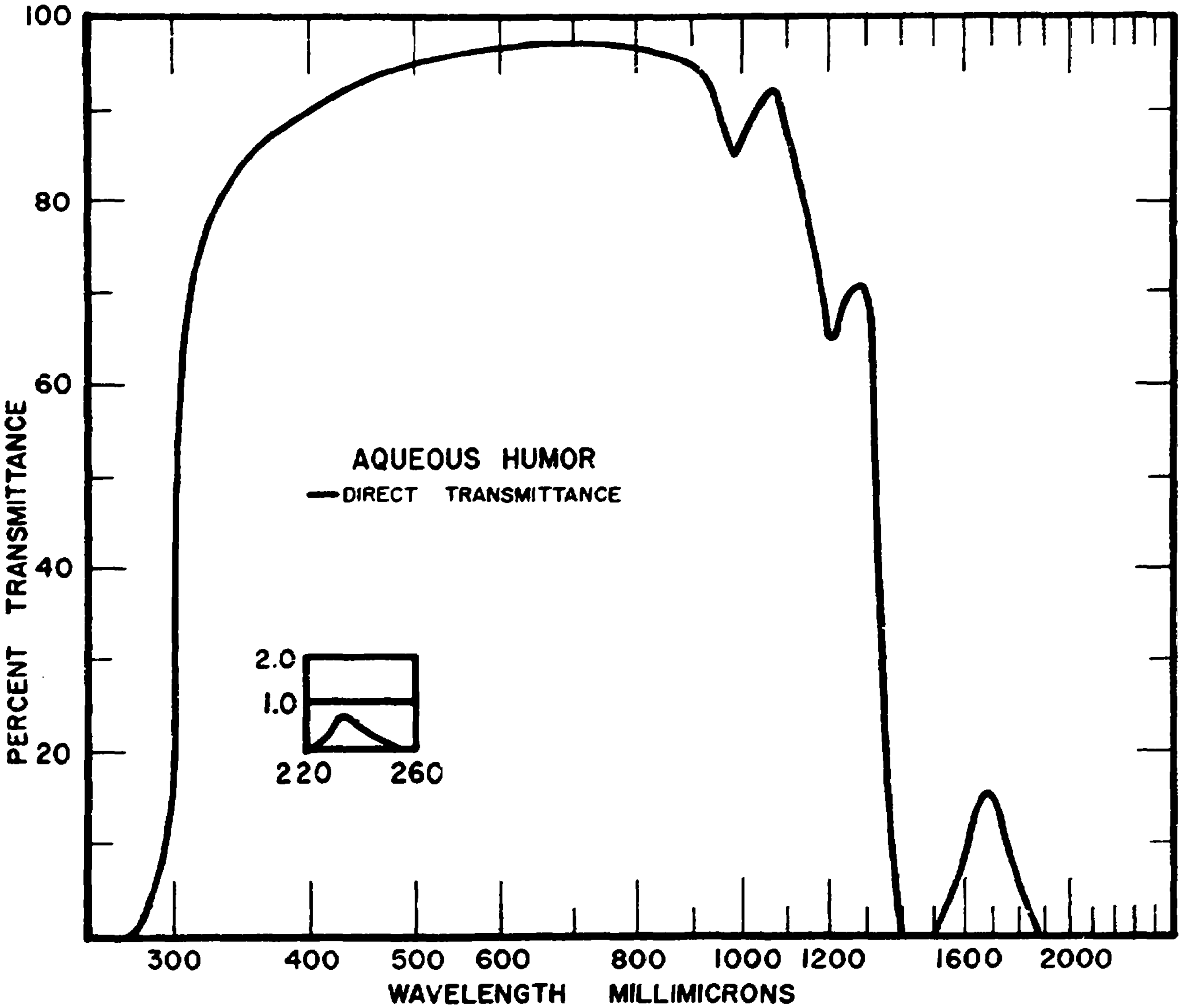


Figure 2. Transmittance of the aqueous humor.

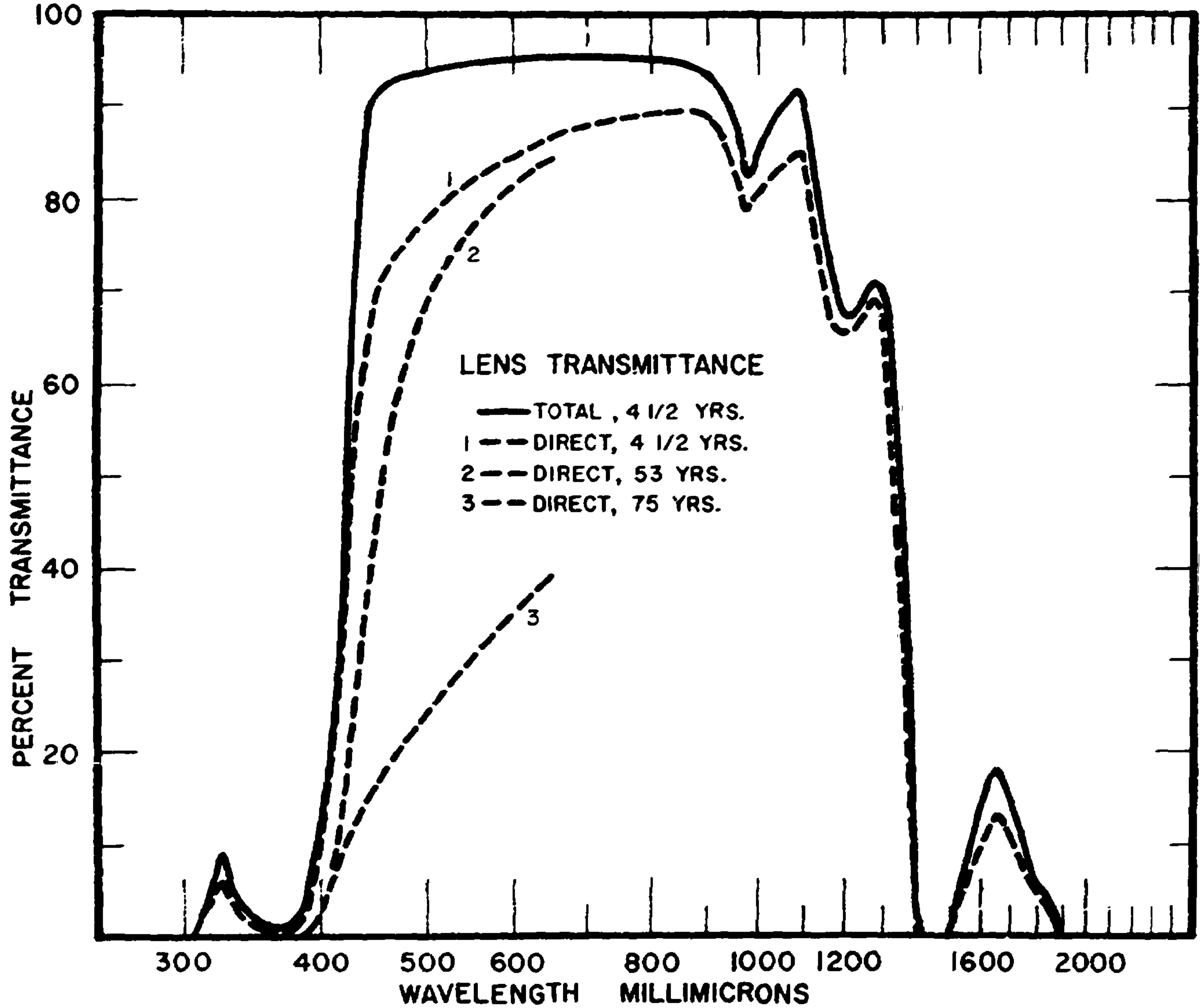


Figure 3. Transmittance of the lens.

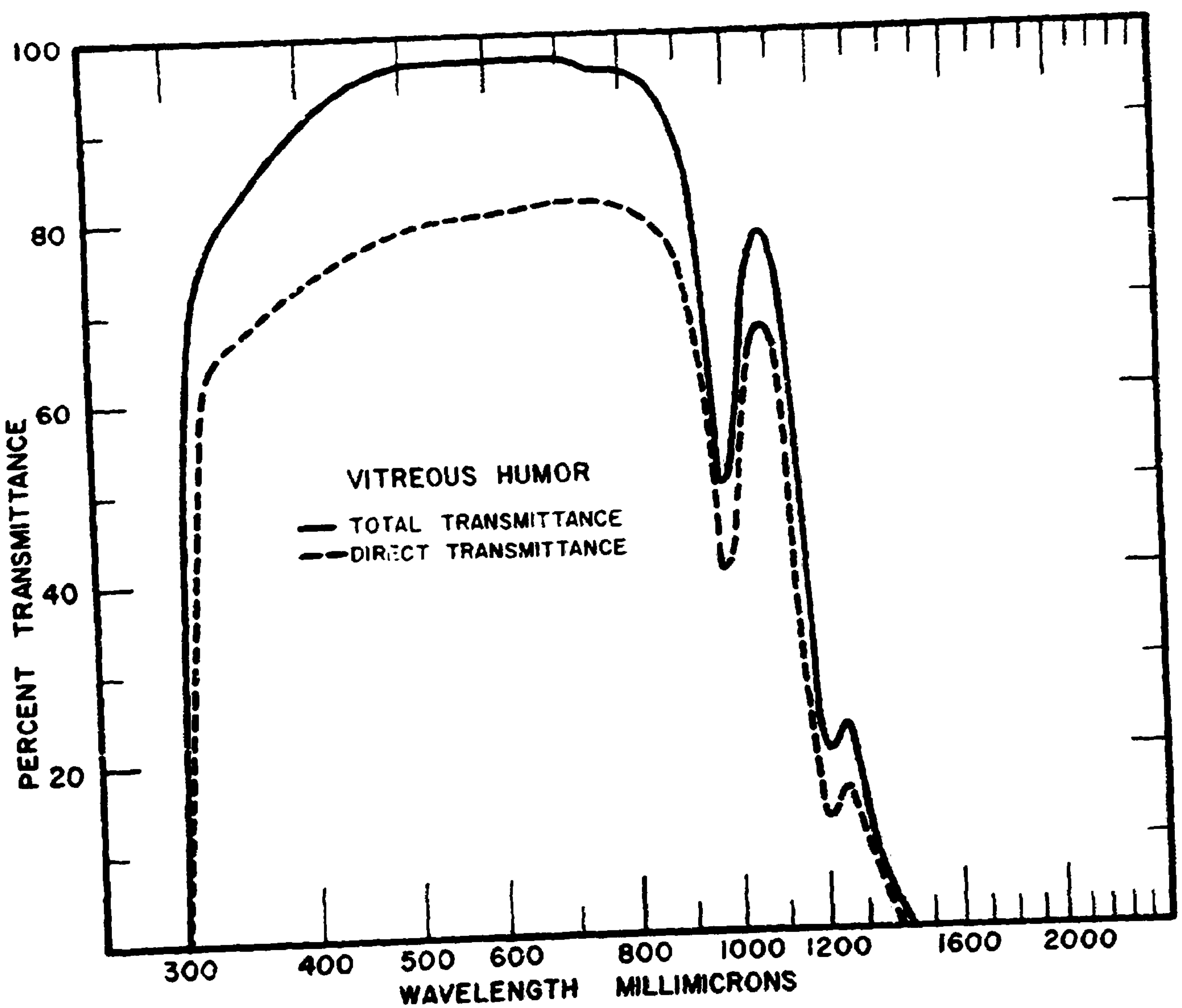


Figure 4. Transmittance of the vitreous humor.

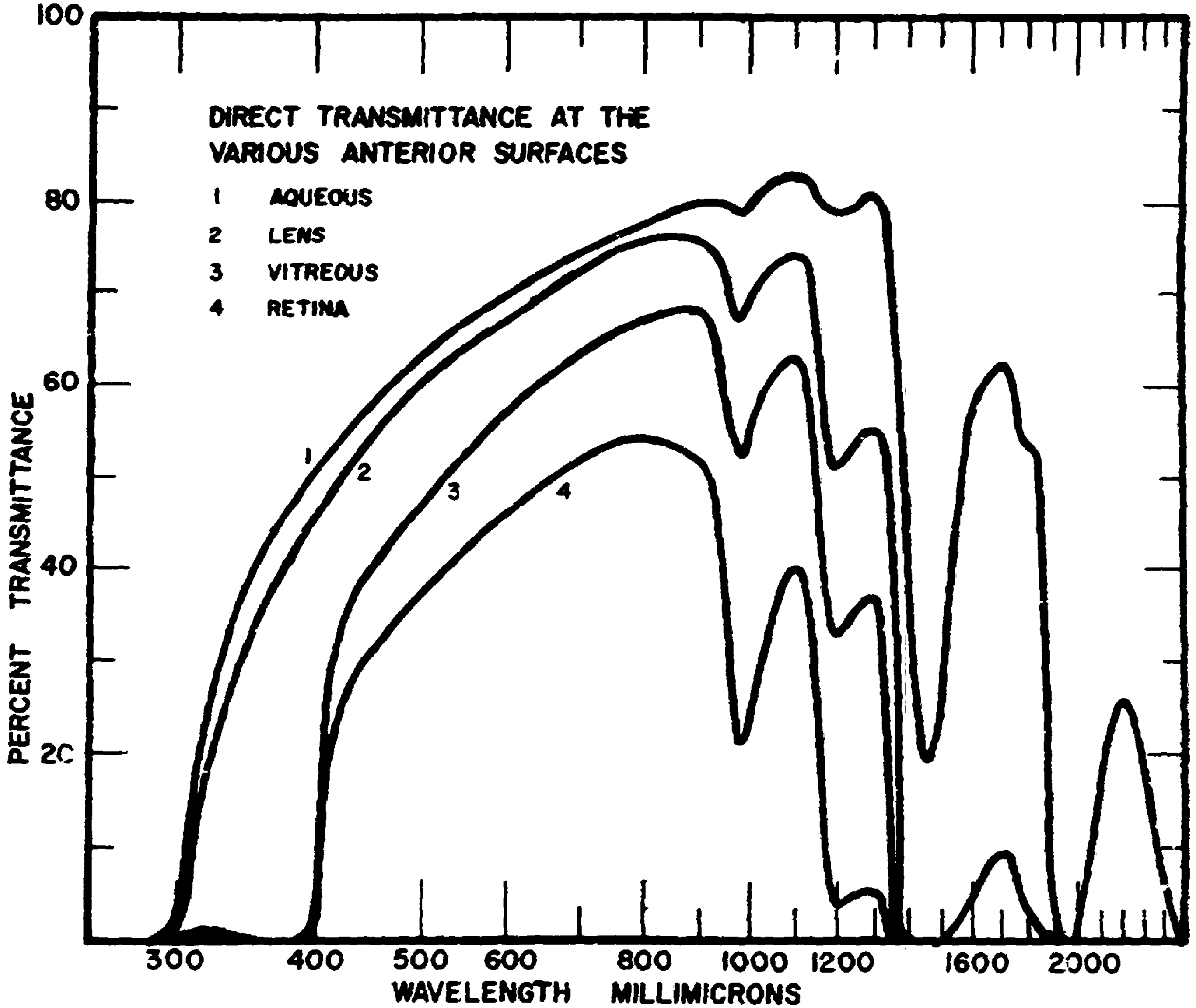
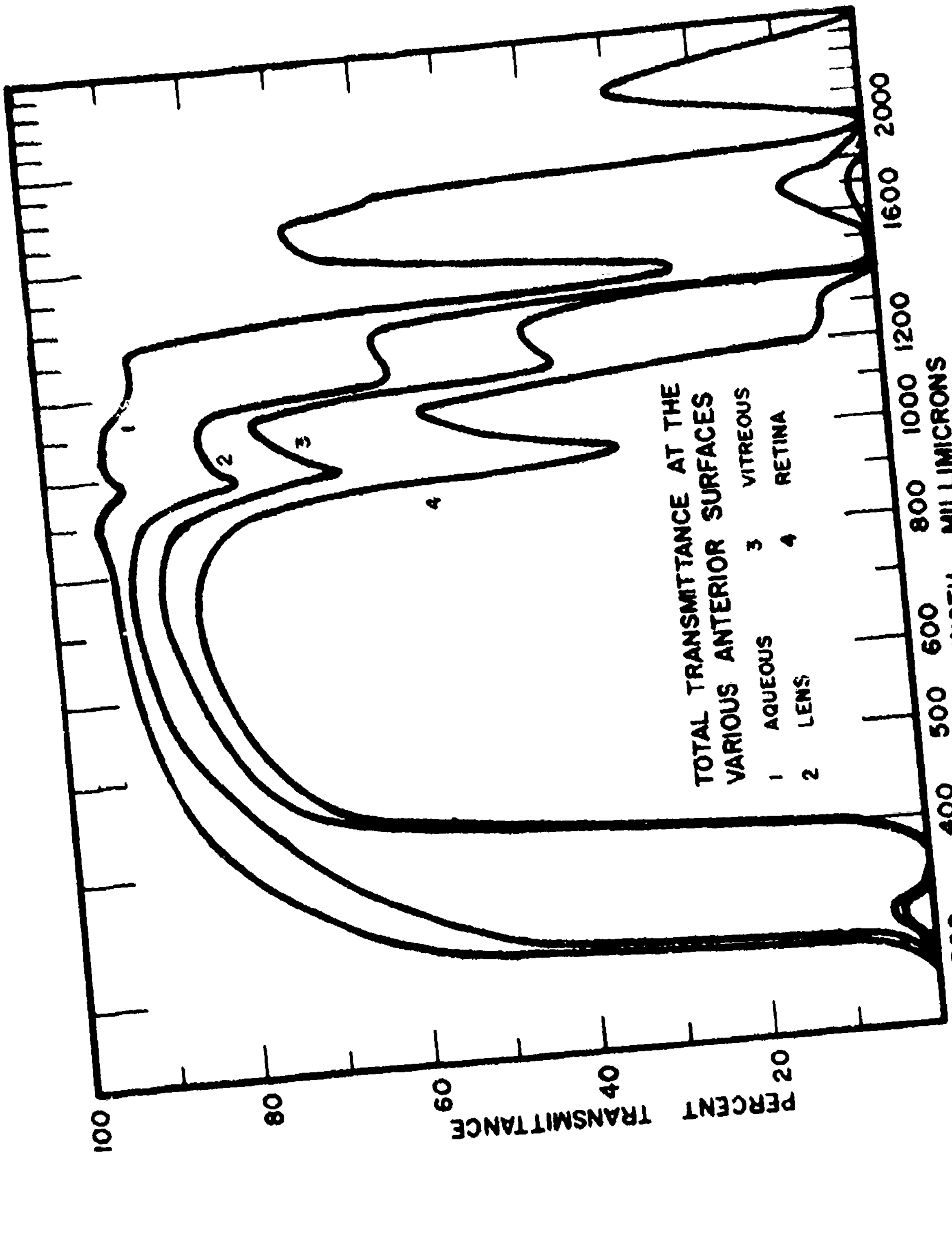


Figure 5. Calculated direct transmittance of the entire eye.


TOTAL TRANSMITTANCE AT THE
VARIOUS ANTERIOR SURFACES
1 AQUEOUS 3 VITREOUS
2 LENS 4 RETINA
PERCENT TRANSMITTANCE
100
80
60
40
20
300
400
500
600
800
1000
1200
1600
2000
WAVELENGTH MILLIMICRONS
1
2
3
4

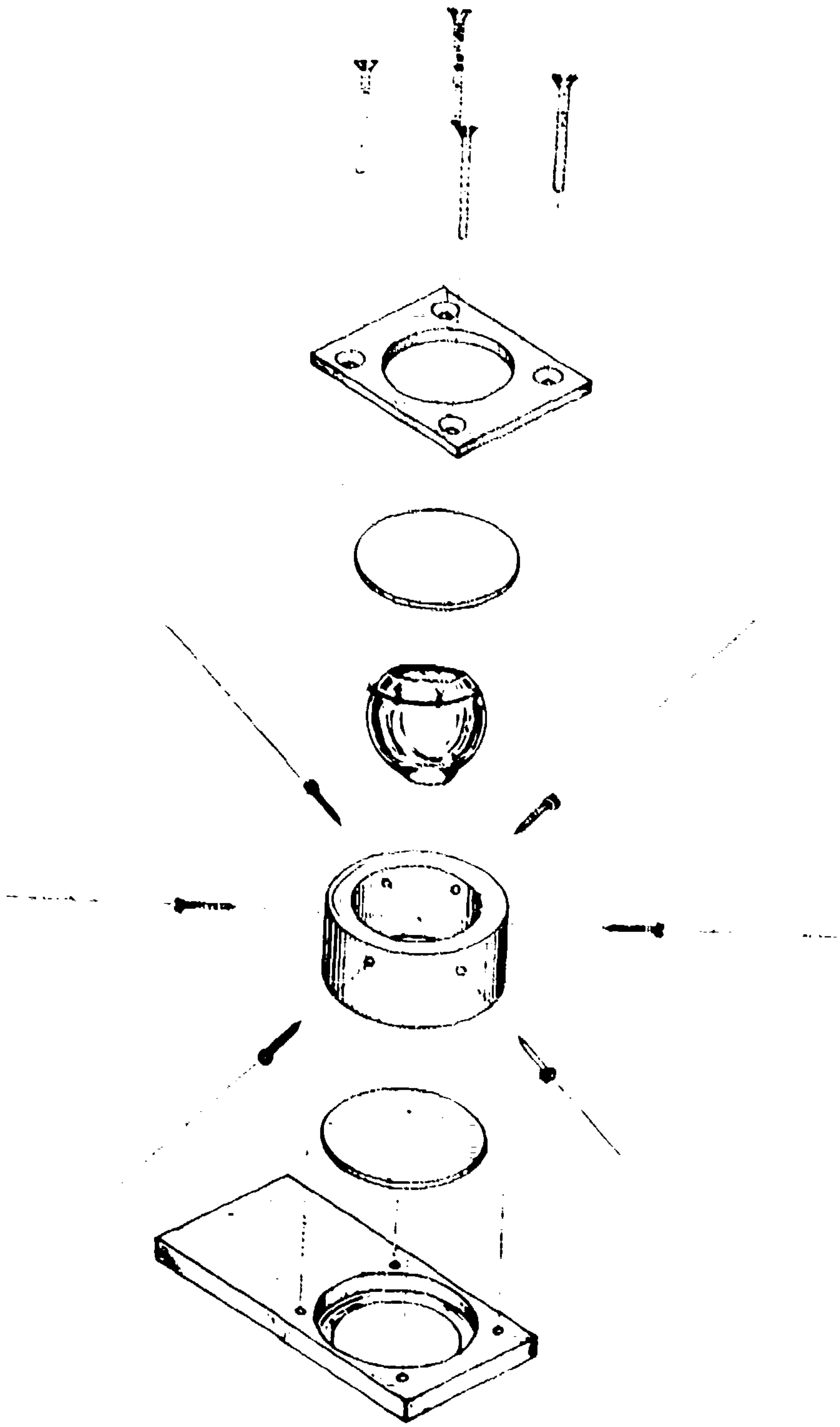


Figure 7. Design of the whole eye cell.

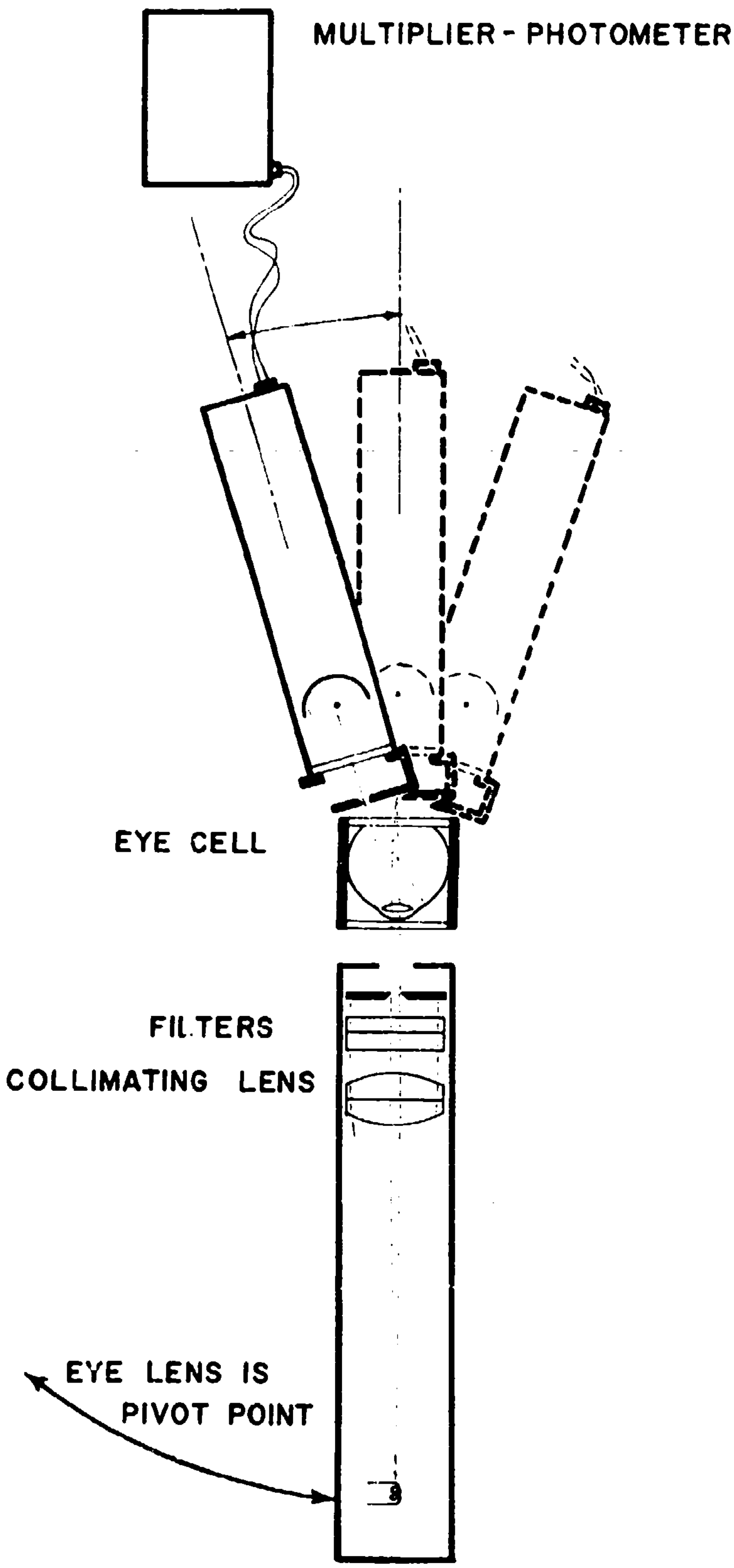


Figure 9. Design of the transmissometer.

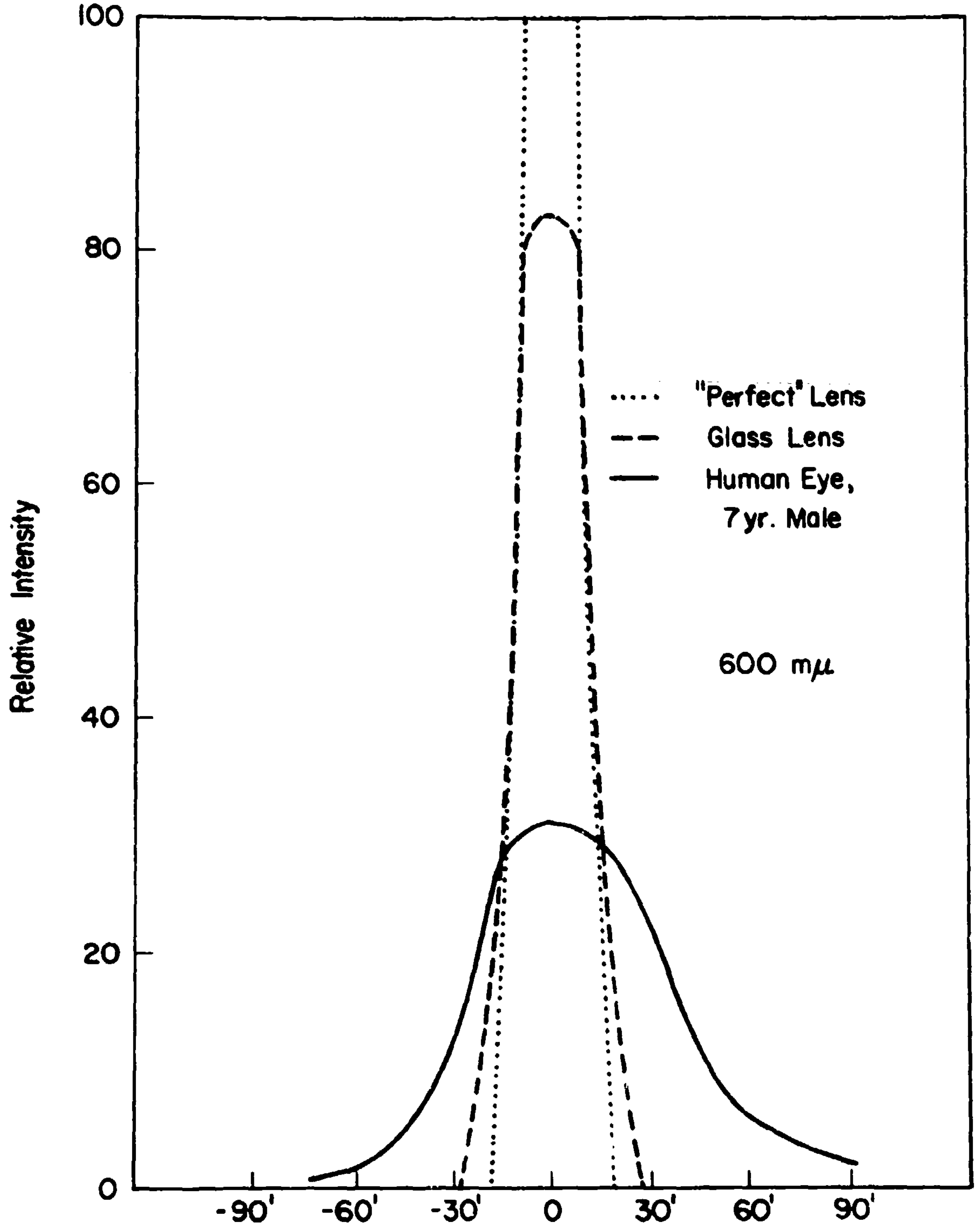


Figure 10. Scatter profile of a human eye, glass lens, and "perfect" lens.

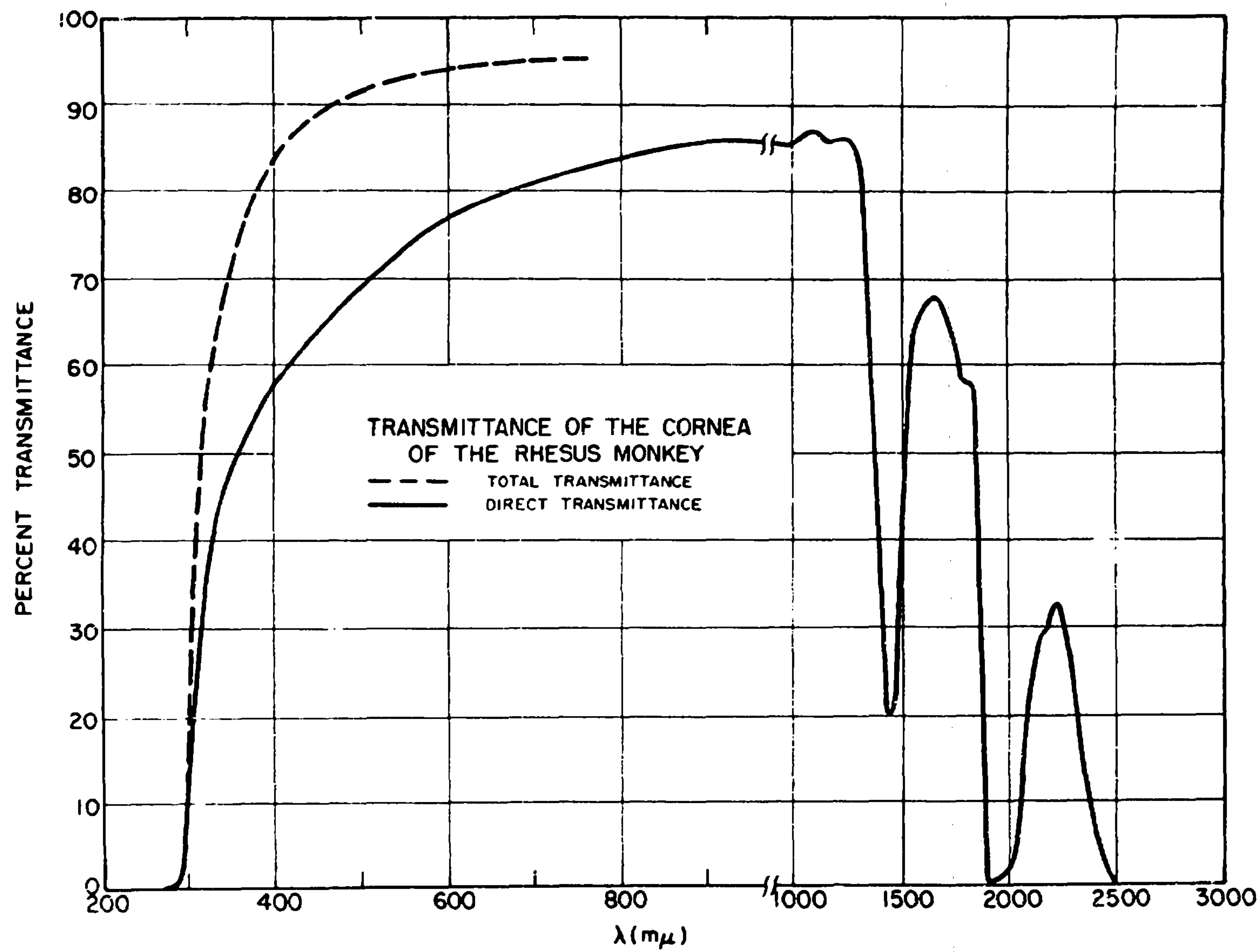


Figure 11. Transmittance of the cornea of the rhesus monkey.

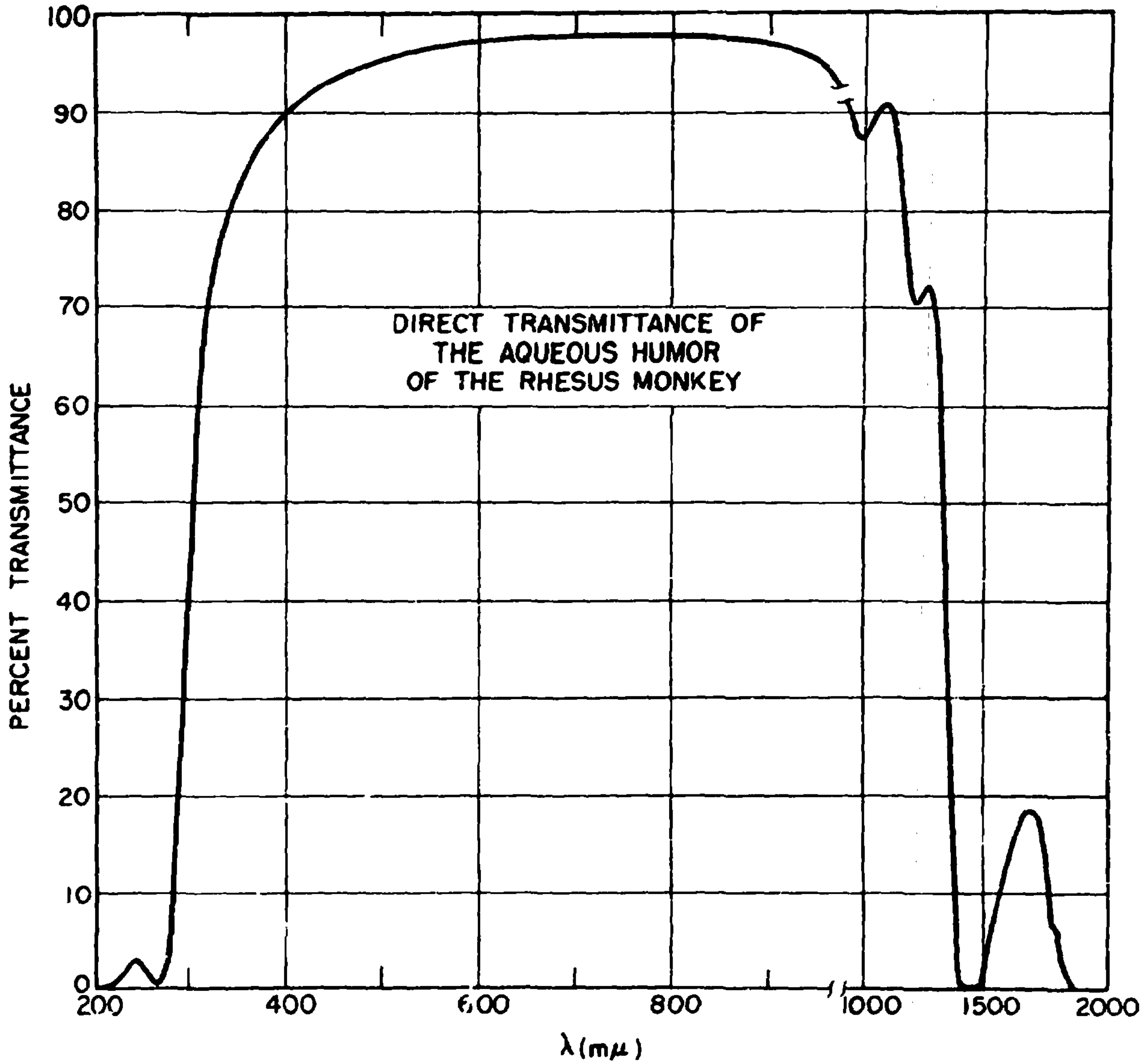


Figure 12. Transmittance of the aqueous humor of the rhesus monkey.

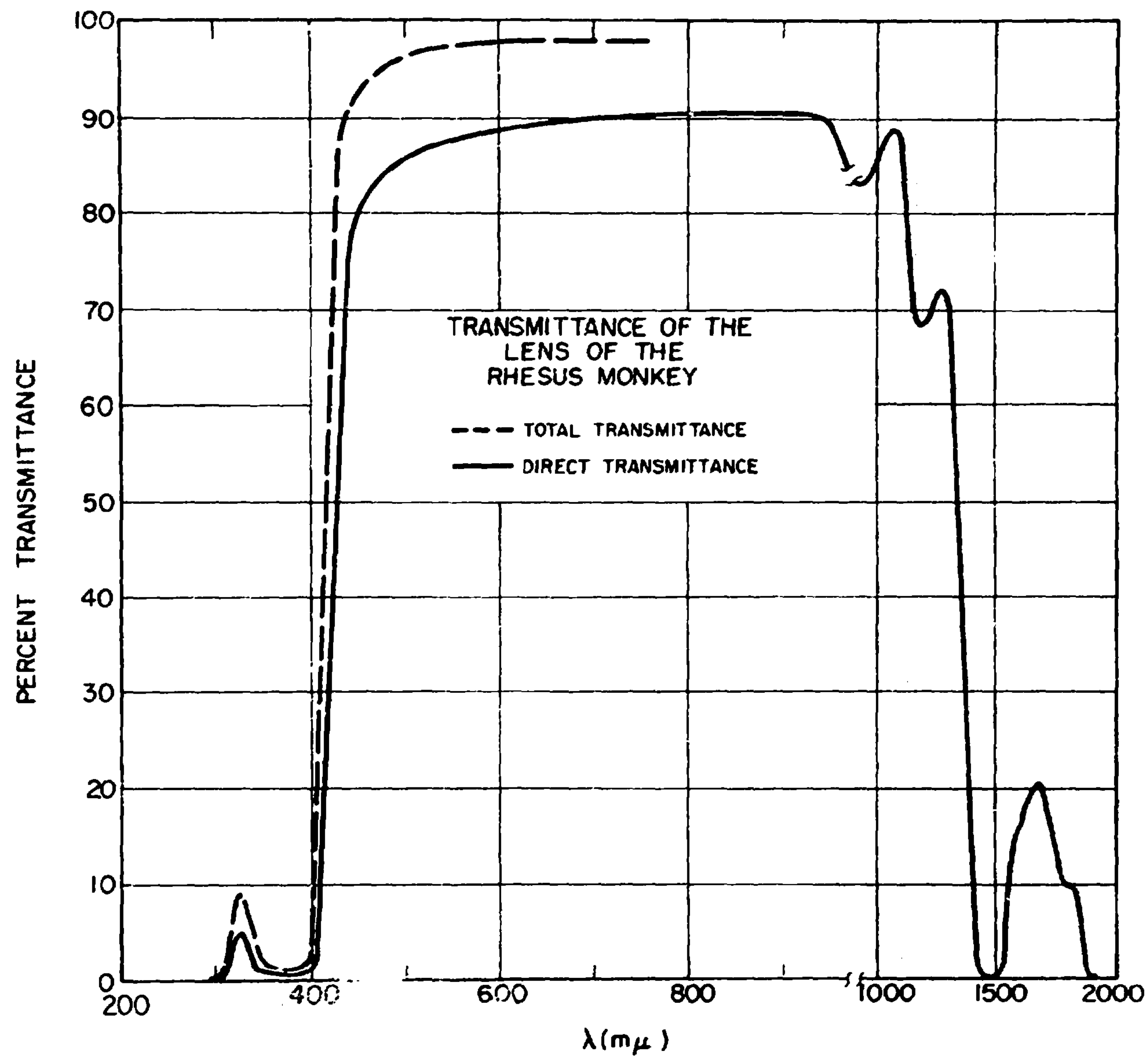


Figure 13. Transmittance of the lens of the rhesus monkey.

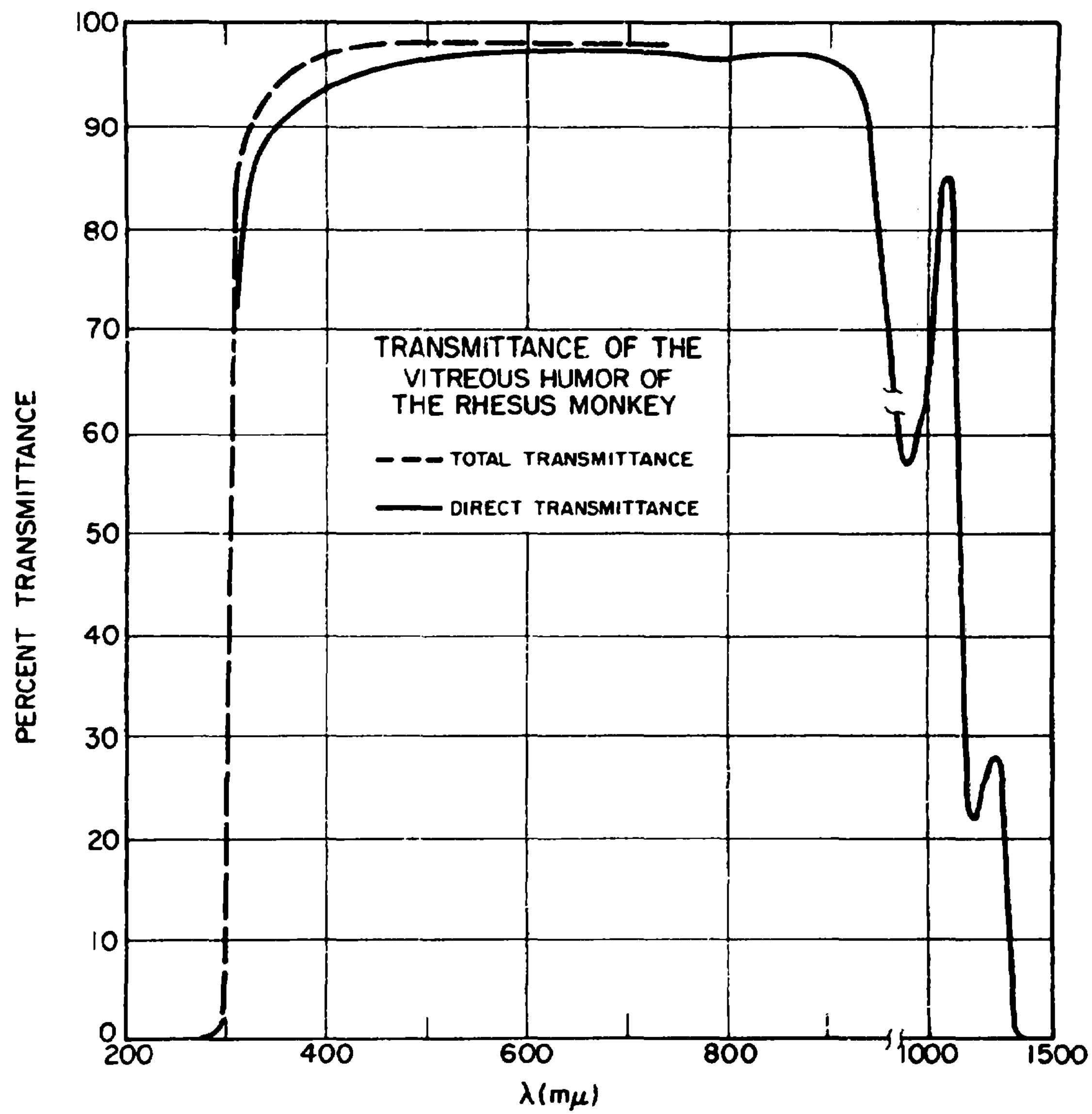


Figure 14. Transmittance of the vitreous humor of the rhesus monkey.

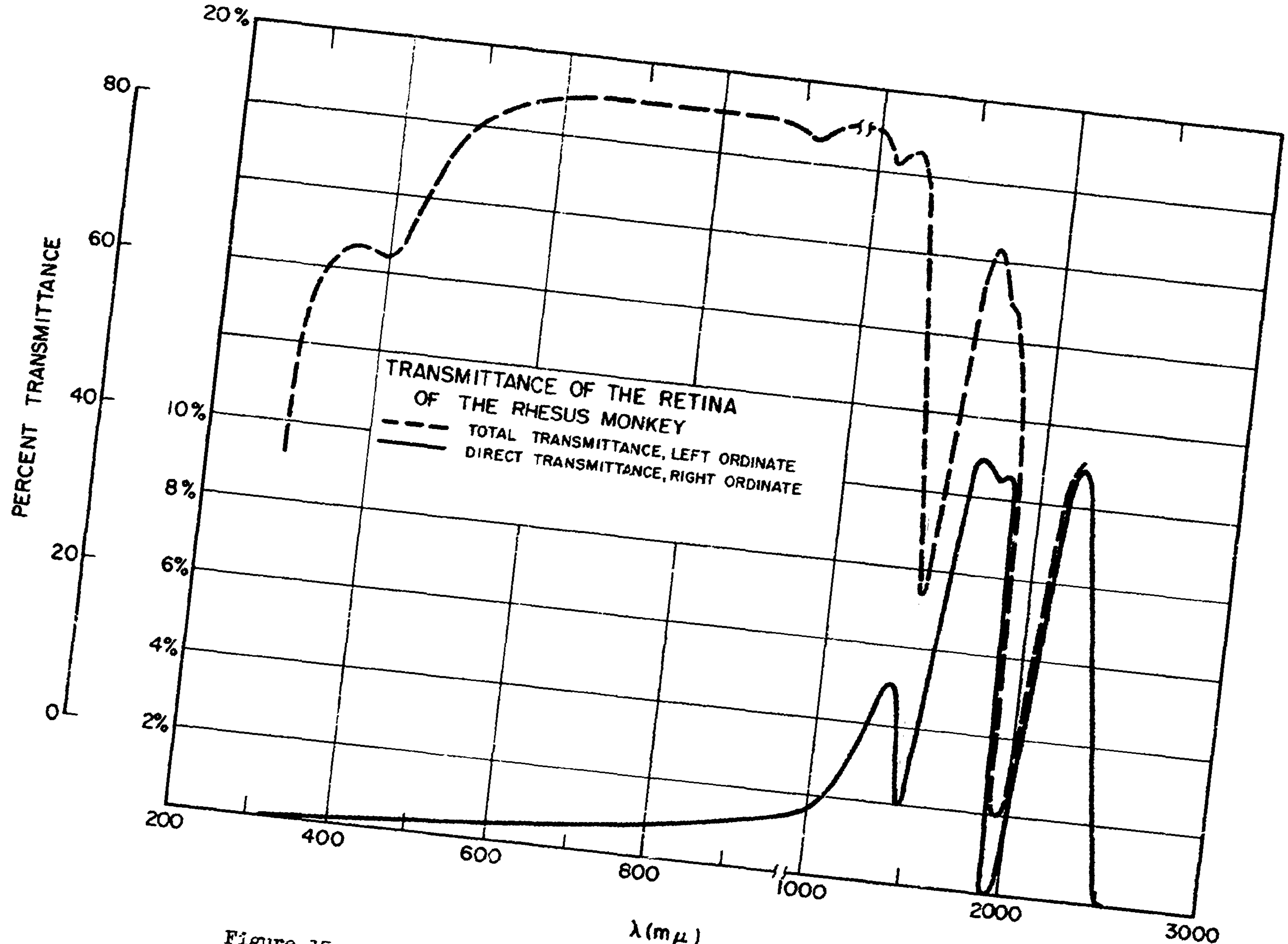


Figure 15. Transmittance of the retina of the rhesus monkey.

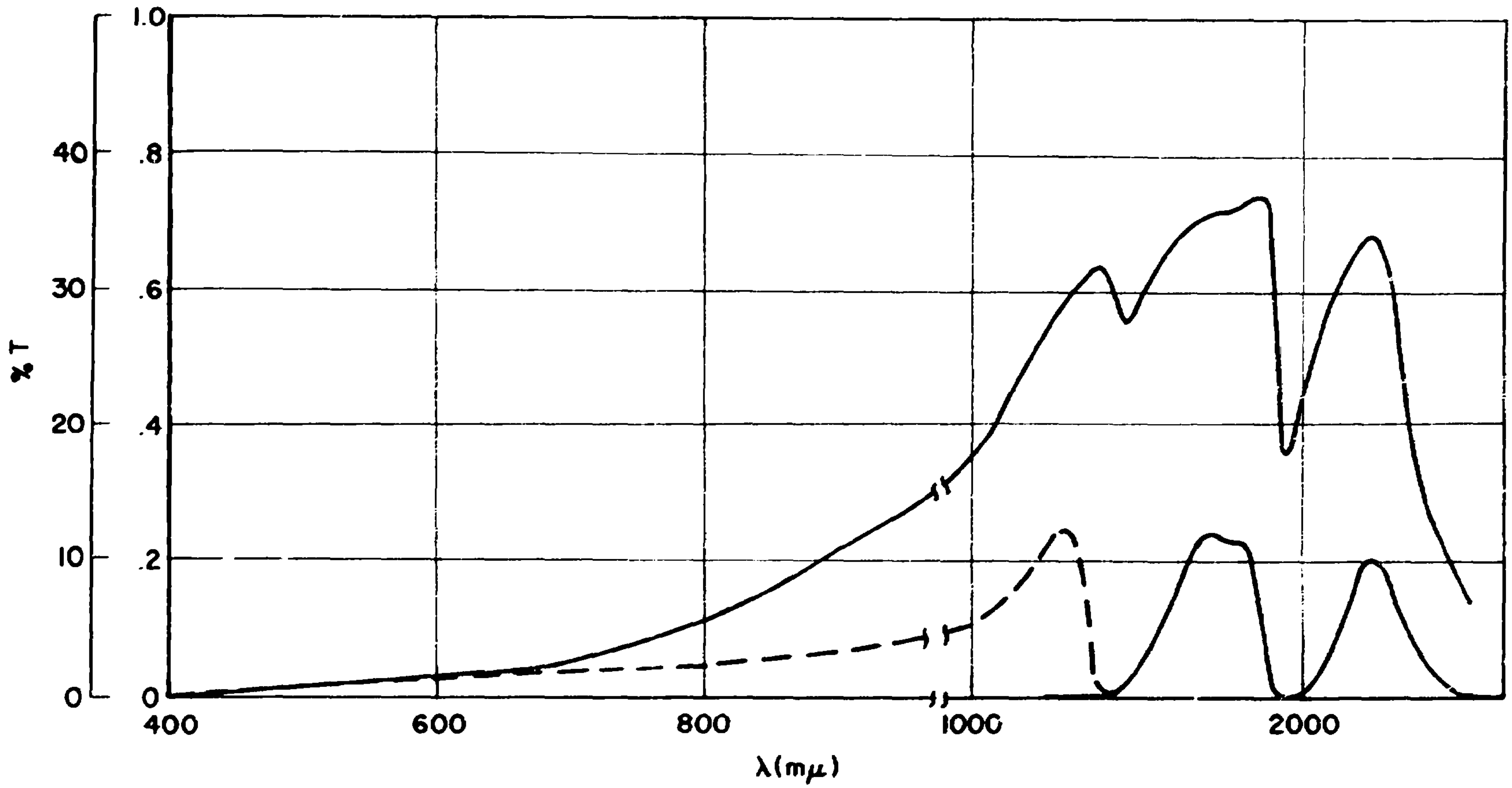


Figure 16. Transmittance of the choroid of the rhesus monkey.

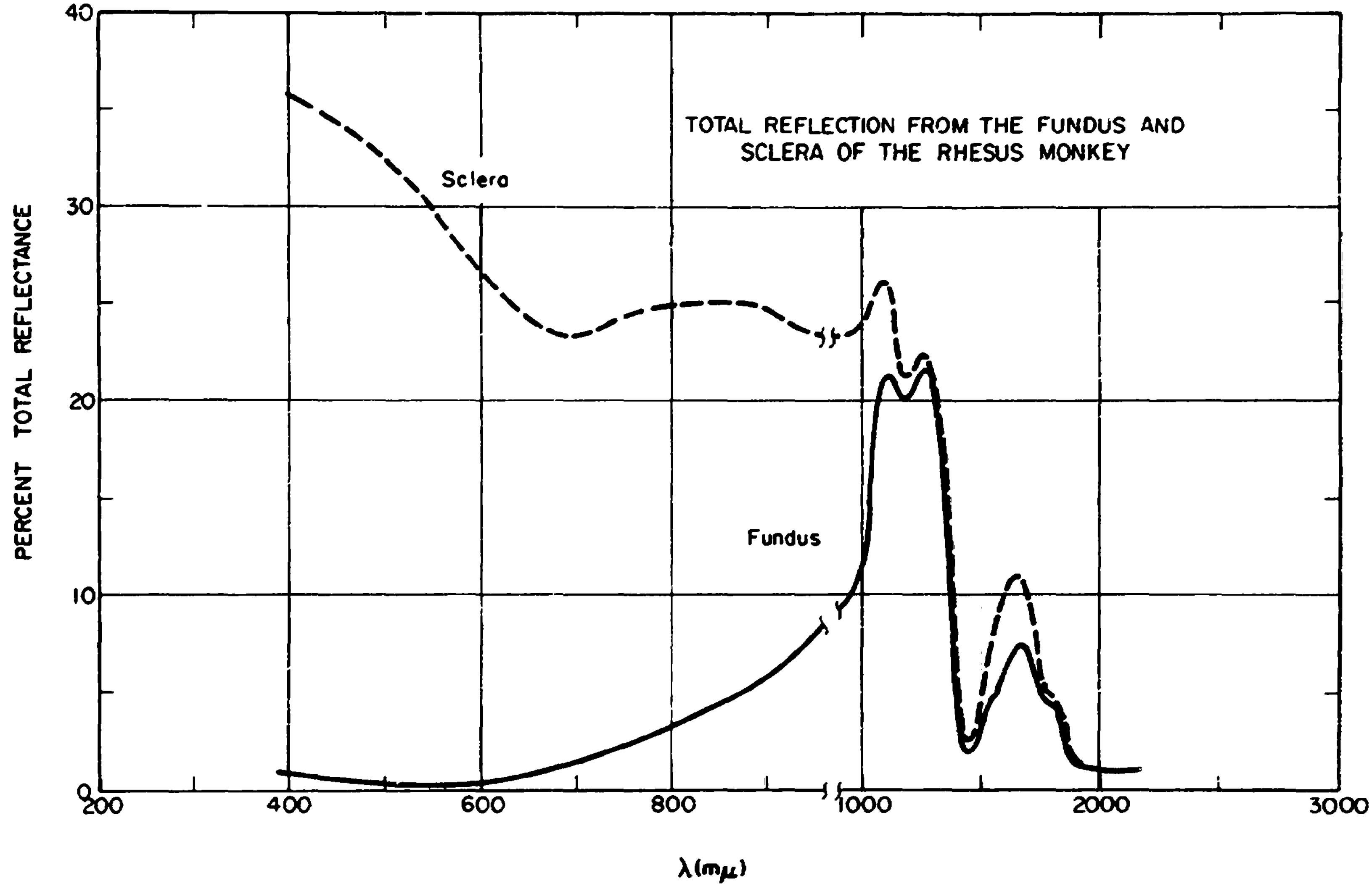


Figure 17. Total reflectance of the fundus and sclera of the rhesus monkey.

TABLE I

PERCENT TRANSMITTANCE OF THE INDIVIDUAL OCULAR MEDIA

Wavelength (mμ)	Cornea Direct	Cornea Total	Aqueous Direct	Lens Direct	Lens Total	Vitreous Direct	Vitreous Total
260	0.0	0.0	< 0.1				
280	< 0.1	< 0.1	0.1			0.0	0.0
300	2.0	8.5	17.5	0.0	0.0	1.0	1.5
320	27.	60.5	78.	6.5	9.	57.	74.
340	35.	68.	83.	2.	2.	64.	79.
360	43.	73.	86.	0.5	0.5	68.	83.
380	48.	78.5	88.5	1.0	1.5	71.	87.
400	52.	82.5	90.	12.	14.	73.	90.
420	55.	84.	91.	56.	63.5	74.5	92.5
440	58.5	85.5	92.	71.	90.	76.	94.
460	61.5	87.	93.5	74.	93.	77.	94.5
480	63.5	88.5	93.5	76.	93.5	78.5	95.5
500	64.5	90.	94.	78.5	94.	79.5	96.
550	67.5	92.	96.	82.	95.	80.	96.5
600	70.5	93.	96.5	85.	95.	80.5	96.5
650	73.	94.	97.5	87.	95.5	81.	97.
700	76.	95.	97.5	88.	96.	81.	96.
750	78.	95.	97.5	88.	96.	81.5	95.5
800	79.5	95.	97.	88.5	96.	81.5	95.
850	81.	95.5	96.5	89.5	96.	79.	94.5
900	82.	95.5	94.5	90.	95.5	75.5	88.5
950	81.5	95.	90.	84.5	90.	59.5	66.
980	81.	93.5	84.5	79.	83.	41.	49.5
1000	82.	94.	87.	80.5	86.	44.5	56.
1100	85.5	94.5	88.	86.	92.	65.	73.5
1200	80.5	91.5	65.5	64.5	66.5	12.	20.5
1300	82.5	90.5	67.	67.	69.5	12.5	16.
1400	40.	59.5	0.5	1.5	4.	< 0.1	2.5
1445	19.	25.	0.0	0.0	0.0		
1500	27.5	33.	0.1	0.2	0.5		
1600	58.5	68.	9.0	9.5	14.5		
1700	64.	71.	15.	11.5	15.5		
1800	56.	62.	6.	5.5	6.5		
1900	3.	5.	0.	0.0	0.0		
1950	0.0	0.5	0.				
2000	1.	3.	< 0.1				
2100	17.	22.	< 0.1				
2200	26.5	31.	0.2				
2300	18.	21.	< 0.1				
2400	5.5	8.	0.0				
2500	0.0	0.5					

TABLE II

PERCENT TRANSMITTANCE THROUGH THE WHOLE EYE

Percent of that radiation incident on the eye reaching the various anterior surfaces

Wavelength	Aqueous		Lens		Vitreous		Retina	
(mμ)	Direct	Total	Direct	Total	Direct	Total	Direct	Total
260								
280	< 0.1	< 0.1	< 0.1	< 0.1				
300	2.	8.5	0.3	1.5	0.0	0.0	0.0	0.0
320	26.5	59.	20.5	46.	1.5	4.	0.9	3.
340	34.5	66.5	28.5	55.	0.5	1.	0.3	1.0
360	42.	71.5	36.	61.5	0.1	0.4	< 0.1	0.4
380	47.	76.5	41.5	67.5	0.4	1.	0.3	0.9
400	51.	80.5	46.	72.5	5.5	10.	4.0	9.
420	54.	82.	49.	74.5	27.5	47.5	20.5	44.
440	57.	83.5	53.	77.	37.5	69.5	28.7	65.5
460	60.	85.	56.	79.5	41.5	74.	32.	70.0
480	62.	86.5	58.5	81.5	44.5	76.	35.	72.5
500	63.	88.	59.5	83.	46.5	78.	37.	75.
550	66.	90.	63.5	86.5	52.	82.	41.5	79.
600	69.5	91.	67.	88.	57.	83.5	46.	80.5
650	71.5	92.	69.5	89.5	60.5	85.5	49.	82.5
700	74.	93.	72.	90.5	63.5	87.	51.5	83.5
750	76.	93.	74.	90.5	65.5	87.	53.5	83.
800	77.5	93.	75.	90.	66.5	86.5	54.	82.
850	79.	93.5	76.	90.	68.	86.5	53.5	81.5
900	80.	93.5	75.5	88.5	68.	84.5	51.5	75.
950	79.5	93.	71.5	83.5	60.5	75.	36.	49.5
980	79.	91.5	66.5	77.5	52.5	64.5	21.5	32.
1000	80.	92.	69.5	80.	56.	69.	25.	38.5
1100	83.5	92.5	73.5	81.5	63.	75.	41.	55.
1200	78.5	89.5	51.4	58.5	33.	39.	4.	8.
1300	80.5	88.5	54.5	59.5	36.5	41.5	4.5	6.5
1400	39.	58.	0.2	0.3	< 0.1	< 0.1	0.0	0.0
1445	18.5	24.	0.0	0.0	0.0	0.0		
1500	27.	32.5	< 0.1	< 0.1	< 0.1	0.0		
1600	57.	66.5	5.	6.	0.5	0.9		
1700	62.5	69.5	9.5	10.5	1.0	1.5		
1800	54.5	60.5	3.	3.5	0.2	0.2		
1900	3.	5.	0.0	0.0	0.0	0.0		
1950	0.0	0.5	0.0	0.0				
2000	1.	3.	0.0	0.0				
2100	16.5	21.5	< 0.1	< 0.1				
2200	26.	30.5	< 0.1	< 0.1				
2300	17.5	20.5	< 0.1	< 0.1				
2400	5.5	8.	0.0	0.0				
2500	0.0	0.5						

TABLE III

SUMMARY OF TOTAL PERCENT TRANSMITTANCE MEASUREMENTS

	Scatter*	466 mμ	566 mμ	666 mμ	800 mμ
August 14, 1963 7-year male	29		79.0 (600 mμ)	82.5	
April 27, 1964 51-year female	40	56.5	79.0	81.0	
June 18, 1964 53-year female	39	38.0	65.0	71.0	71.0
October 22, 1964 45-year male	37	46.0	69.0	84.0	64.0
February 19, 1965 52-year male	30	41.0	69.0	79.0	67.0
Calculated Transmission (reference 2)		68	78	82	81

*Percent of 566 mμ scattered outside of a 1 degree cone, except 7-year male, which was measured at 600 mμ.

TABLE IV

PERCENT TRANSMITTANCE OF THE INDIVIDUAL OCULAR MEDIA OF THE RHESUS MONKEY

Wavelength	Cornea		Aqueous	Lens		Vitreous	
(mμ)	Direct	Total	Direct	Direct	Total	Direct	Total
200			< 0.1				
220			.2				
240			2.5				
260			1.5				
280	< 0.1	< 0.1	2.0			< 0.1	< 0.1
300	10.	16.	40.	< 0.1	0.5	15.	15.
320	34.	54.	70.	5.	9.	82.	90.
340	45.	67.5	80.	1.	3.	88.5	93.
360	51.5	74.	84.	.5	1.	90.5	94.5
380	54.	80.	87.5	.5	1.	92.5	96.
400	67.5	83.5	89.5	2.	10.	93.5	97.
420	60.5	96.	91.5	35.	62.	94.	97.5
440	63.	88.	93.	71.	90.5	95.	97.5
460	65.	90.	93.5	82.	93.	95.5	98.
480	67.	91.	94.5	84.5	95.5	96.	98.
500	69.	91.5	95.	86.5	96.5	96.5	98.
550	73.5	92.5	96.5	87.5	97.5	97.	98.
600	77.	94.	97.5	89.	97.5	97.5	98.
650	79.	94.5	97.5	89.5	98.	97.5	98.
700	81.	95.	97.5	90.	98.	97.	98.
750	82.5	95.	98.	90.5		97.	98.
800	84.		98.	90.5		96.5	
850	85.		97.5	91.		97.	
900	86.		97.	91.		96.5	
950	86.		95.	89.		80.	
980	85.5		90.5	83.		57.	
1000	85.5		88.	85.5		63.5	
1100	87.		90.5	88.		77.	
1200	86.		70.5	68.5		22.5	
1300	83.5		65.	70.		23.	
1400	38.0		0.5	5.		< 0.1	
1445	20.		0.1	0.1			
1500	38.		0.5	0.5			
1600	66.5		12.5	16.5			
1700	66.5		19.	18.5			
1800	58.		7.	9.5			
1900	0.5		< 0.1	< 0.1			
1950	0.5						
2000	2.0						
2100	22.5						
2200	32.						
2300	23.						
2400	16.5						
2500	0.5						

TABLE V

PERCENT TRANSMITTANCE THROUGH THE WHOLE EYE OF THE RHESUS MONKEY

Percent of that radiation incident on the eye reaching the various anterior surfaces

Wavelength	Aqueous		Lens		Vitreous		Retina	
(mμ)	Direct	Total	Direct	Total	Direct	Total	Direct	Total
260			0.0					
280	< 0.1	< 0.1	0.0					
300	10.	16.	4.	6.5	0.0	< 0.1	0.0	0.0
320	33.	53.	23.	38.	1.0	3.5	0.8	3.0
340	44.	66.	35.	53.	0.4	1.5	0.3	1.5
360	50.	72.	42.	60.5	0.2	0.6	0.2	0.6
380	52.5	78.	46.	68.	0.2	0.7	0.2	0.7
400	66.	81.5	59.	73.	1.0	7.5	1.0	7.5
420	59.	94.	54.	86.	19.	53.5	18.	52.
440	61.5	86.	57.	80.	40.5	72.5	38.5	70.5
460	63.5	88.	59.5	82.5	49.	76.5	47.	75.
480	65.5	89.	62.	84.	52.5	80.	50.5	78.5
500	67.5	89.5	64.	85.	55.5	82.	53.5	80.5
550	71.5	90.5	69.	87.5	60.5	85.5	58.5	84.
600	75.	92.	73.	89.5	65.	87.	63.5	85.5
650	77.	92.5	75.	90.	67.	88.	65.5	86.
700	79.	93.	77.	90.5	69.5	88.5	67.5	86.5
750	80.5	93.	79.	91.	71.5		69.5	
800	82.		80.5		73.		70.5	
850	83.		81.		73.5		71.5	
900	84.		81.5		74.		71.5	
950	84.		80.		73.		58.5	
980	83.5		75.5		62.5		35.5	
1000	83.5		73.5		63.		40.	
1100	85.		77.		68.		52.5	
1200	84.		59.		40.5		9.	
1300	81.5		53.		37.		8.5	
1400	37.		18.5		3.5		0.0	
1445	19.5		< 0.1		0.0			
1500	37.		0.2		0.0			
1600	65.		8.		1.5			
1700	65.		12.5		2.0			
1800	56.5		4.		0.4			
1900	0.5		< 0.0		< 0.0			
1950	0.5							
2000	2.							
2100	22.							
2200	31.							
2300	22.5							
2400	16.							
2500	0.5							

TABLE VI

PERCENT TRANSMITTANCE OF THE RETINA AND CHOROID OF THE RHESUS MONKEY

Wavelength	Retina		Choroid	
(mμ)	Direct	Total	Direct	Total
300	< 0.1	45.		
325	< 0.1	59.		
350	0.1	63.		
375	0.1	63.		
400	0.1	62.		
425	0.1	65.5		< 0.1
450	0.2	72.		0.1
475	0.2	77		0.5
500	0.2	80.5		11.0
550	0.3	83.		1.0
600	0.4	84.5		1.5
650	0.5	85.		2.0
700	0.6	85.		2.5
750	0.7	85.		4.0
800	0.8	84.5		5.5
850	1.0	85.		8.0
900	1.1	84.		11.
950	1.3	84.5		14.
1000	1.6	85.		17.
1100	2.3	81.		21.5
1200	3.3	83.		26.
1300	4.8	71.		30.
1400	3.7	40.		31.
1445	2.0	27.	0.00	27.5
1500	3.7	35.5	0.03	29.
1600	8.0	66.	0.14	33.5
1700	10.9	69.5	0.23	35.5
1800	10.5	62.	0.22	36.
1900	< 0.1	23.	0.02	34.
1950	< 0.1	< 0.1	0.00	18.
2000	2.0	5.	< 0.01	23.
2100	7.4	32.5	0.09	30.5
2200	10.9	46.	0.20	34.5
2300	8.0		0.11	22.5
2400	3.5		0.03	11.5
2500	< 0.1		< 0.01	7.
2600	0.0			

TABLE VII

PERCENT REFLECTANCE OF THE FUNDUS AND SCLERA OF THE RHESUS MONKEY

Wavelength (mμ)	Fundus	Sclera
400	0.8	36.
450	0.5	34.
500	0.3	32.5
550	0.3	30.
600	0.4	26.5
650	0.8	24.
700	1.5	23.
750	2.3	24.
800	3.1	25.
850	4.3	25.
900	5.8	24.5
950	8.	23.5
1000	10.5	24.
1100	22.5	26.
1200	20.5	21.5
1300	20.5	21.5
1400	5.	7.5
1445	2.	2.5
1500	3.	4.
1600	6.	10.
1700	7.	10.
1800	4.5	5.
1900	1.5	1.5
2000	1.	1.
2100	1.	1.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY USAF School of Aerospace Medicine Aerospace Medical Division (AFSC) Brooks Air Force Base, Texas 78235

13. ABSTRACT

The spectral transmittance of ultraviolet, visible, and near infrared light through the eye of humans and monkeys has been measured. Using freshly enucleated eyes, the transmittances of each component part (cornea, aqueous humor, lens, vitreous humor, retina and choroid) were determined for the wavelength range from 0.22 to 2.8 μ (microns). Two types of measurements were made: the first to measure the total light transmitted (direct and scattered) at each wavelength and the second to measure the percent transmittance of that light passing directly through the various media without absorptior or scattering. The results show that: (a) the transmission of ultraviolet radiation decreases with the age of the eye; (b) the transmission of infrared radiation appears to be independent of the age; and (c) the maximum total transmittance of the whole eye, about 83%, is obtained in the region from 600 to 850 mμ (millimicrons). The spectral reflectance of the fundus and sclera of the rhesus monkey was measured, with the former reflecting less than 2% in the visible but increasing to 20% in the infrared (1200 mμ). The sclera reflects 20 to 30% through the visible and infrared out to 1200 mμ. The The forward scattered light outside of 1 degree as measured on the whole human eye was 35% ± 5% at 566 and 666 mμ.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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